An Investigation of Turbulent Heat Exchange in the Subtropics

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LONG-TERM GOALS

The long-term goal is to improve our understanding of heat and moisture exchange in the tropics through direct estimates of the fluxes and their related mean variables. The flux of heat across the coupled boundary layers is primarily accomplished by small-scale processes that are parameterized in numerical models. The ultimate goal is to improve the Navy's predictive capabilities in the tropics through an improved understanding of the processes driving the Madden-Julian Oscillation (MJO).

OBJECTIVES

The primary objective of this research is to improve the surface flux parameterization for latent and sensible heat used in these models and observational process studies. We will collaborate with researchers from NCAR, NOAA/ETL, Oregon State University, and other institution to investigate the relationship between boundary layer structure and surface forcing during an MJO event. This will be accomplished through measurements collected from a research vessel that will conduct surveys during two 30-40 cruises to investigate air-sea interaction during periods when conditions are favorable for MJO formation (Madden and Julian, 1994). The measurement will include surface meteorological and atmospheric vertical structure and collaboration with numerical modelers and other observational components of the program. **The principle hypothesis of this research is that improved observations and parameterizations of latent and sensible heat fluxes, which is a primary source of energy for these convective systems, will improve our ability to simulate and predict the MJO.**

APPROACH

The PI (Edson) lead the effort to deploy a turbulent and radiative flux package, mean meteorological sensors and GPS rawinsonde systems aboard the research vessel.

Flux Measurements: The PI (Edson) will deploy his high-power version of the Direct Covariance Flux System (DCFS) aboard the research vessel used in the field program alongside a suite of instruments to measure the short and longwave radiative fluxes, wind speed and direction, temperature, pressure, humidity, and precipitation. The DCFS (Edson et al., 1998) has been used in a number of field programs and would provide estimates of the momentum, sensible heat and latent heat fluxes during ship-based surveys. The PI has recently purchased a newly developed LI-COR LI-7200 infrared gas analyzer that is expected to improve the latent heat flux estimates. This new unit will be run alongside the LI-7500 that has been successfully deployed in previous investigations.

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The DCFS will be combined with their associated means and oceanic variables to:

- Provide direct estimates of the air-sea fluxes driving boundary layer evolution and mixed layer response over an annual cycle of MJO events.
- Quantify the spatial variability of atmospheric forcing in the study area.
- Investigation the temporal relationship between SST anomalies, convection (e.g., using satellite date or in situ radiation measurements as surrogates), and latent heating.
- Improve bulk parameterizations of latent and sensible heat fluxes for process studies and boundary condition in numerical models.

The DCFS will allow use to investigate the exchange of sensible and latent heat between the atmosphere and ocean using the direct covariance method. This method correlates fluctuations in the vertical velocity, w', with fluctuations in the sensible heat, $\rho_a c_p T'$, and latent heat, $\rho_a L_v q'$, per unit volume:

$$Q_{sen} = \rho_a c_p \overline{w'T'} \tag{1}$$

$$Q_{lat} = \rho_a L_v \overline{w'q'} \tag{2}$$

where ρ_a is the density of air, c_p is the specific heat of air, L_v is the latent heat of vaporization, T' and q' are temperature and specific humidity fluctuations, respectively; and the overbar denotes a time average ranging between 10-30 minutes for turbulent fluxes. The sensors must be capable of accurately measuring fluctuation at approximately 2 Hz to capture the total flux near the air-sea interface.

Unfortunately, this direct method is generally difficult to implement over the ocean due to platform motion, flow distortion and sensor limitations. Instead, oceanographers and meteorologists often rely on bulk formula such as the COARE 3.0 algorithm (Fairall et al., 1996; 2003) that relates the fluxes to more easily measured averaged wind speed, temperature and humidity. These averaged variables are related to the flux through transfer coefficients. This same approach is commonly used to parameterize the surface fluxes in forecast models from variables resolved by the model. For example, based on the dimensional arguments, the exchange of sensible and latent heat at the ocean surface is expected to go as the wind speed time the air-sea temperature and humidity differences, respectively:

$$Q_{sen} \cong -\rho_a c_p C_H U_r \Delta\Theta \tag{3}$$

$$Q_{lat} \cong -\rho_a L_v C_E U_r \Delta Q \tag{4}$$

where C_H and C_E are the transfer coefficients for heat and mass known as the Stanton and Dalton numbers, respectively; U_r is the wind speed relative to water (i.e., the wind speed-current difference); and $\Delta\Theta$ and ΔQ are the mean air-sea potential temperature and specific humidity. The uncertainty in the transfer coefficients for heat and mass remains one of the main obstacles to accurate numerical forecasts. Improvement of these transfer coefficients is a primary objective of this research.

Boundary-Layer Measurements: The PI (Edson) proposes to launch GPS rawinsondes to provide co-located observations of the vertical structure in the atmospheric boundary layer (ABL). The PI will collaborate with the ISS group at NCAR to conduct these soundings and plans to deploy his Vaisala GPS system along-side the NCAR/ISS GAUS balloon-borne rawinsonde sounding system. This will allow us to launch rawinsondes at least 4 times per day with more frequent launches during intensive operating periods; e.g., before, during and after passage of active convection and westerly wind bursts. The 1-D profiles collected from the rawinsonde would complement the 2-D structure measured by the autonomous and manned aircraft. The ABL measurements would be used to:

- Provide a time series of the ABL height, z_i, during the IOP.
- Improve the "gustiness" parameterization in bulk formulae, which drive the surface fluxes in convective conditions.
- Investigate the low-level convergence/divergence patterns in the wind temperature and humidity fields and their relationship to SST gradients and deep convection.
- Provide observation of the ABL structure for assimilation in and/or validation of atmospheric models.

For example, the ABL measurements will be used to investigate the role of the convective velocity in our heat flux parameterizations. For example, the COARE 3.0 algorithm attempts to account for the role of gustiness in driving air-sea exchange by including a gustiness parameter in the wind speed calculation:

$$U_r^2 = u^2 + (\beta w_*)^2 = u^2 + \left[\beta\left(\frac{g\,\overline{wT_v}}{T\,z_i}\right)\right]^2 \tag{5}$$

where u is the average of the relative velocity, and w_* is the convective scaling velocity as defined in the right-hand-term where z_i is the boundary layer height and β is an empirical constant of order 1 whose value depends on temporal scales used to compute the averages (Fairall et al. 1996). This parameter accounts for the fact that while the time average velocity under convective systems may be small (i.e., even strong back and forth wind gusts could approximately average to zero in a vector sense), the variance in this velocity captured in the average wind speed (and the associated wind shear) is not. These convectively driven gusts drive air-sea exchange at low winds. However, most wind observations from surface moorings are based on vector averaged wind, which removes both undesirable platform motion and desirable gustiness. This motivated the inclusion of a gustiness parameter in the COARE algorithm. The DCFS can measure the wind speed after correction for the platform motion. Therefore, estimates of the boundary layer height from the soundings can be used with the wind speed and buoyancy flux to investigate the role of the convective velocity on air-sea exchange and improve this parameterization.

WORK COMPLETED

In preparation for the field work in the fall of 2011, the PI has combined heat flux estimates from a number of recent field programs to look at the behavior of the transfer coefficients from prior experiments. These field programs including the ONR sponsored CBLAST program (Edson et al. 2007) and the NSF sponsored CLIMODE (Marshall et al. 2009) and GASEX programs. The CBLAST-LOW experiments were primarily conducted in low to moderate winds while the CLIMODE and GASEX experiments focused on air-sea interactions at moderate to high winds. The combined data set therefore covers a wide range of wind and stability conditions. For example, near surface winds of 15 m/s were commonly encountered over the North Atlantic during CLIMODE and the data set includes wind events with speeds over 25 m/s. These high wind events drive surface stresses that routinely exceed 1.0 N/m^2 and combined latent and sensible heat fluxes from the ocean into the atmosphere that exceed 1200 W/m^2. These enormous heat fluxes are driven by high winds and large air-sea temperature and humidity differences encountered over the Gulf Stream during cold air outbreaks. The CBLAST-LOW program collected 3 months of data from an Air-Sea Interaction Tower (ASIT) under low to moderate wind conditions. To data, the CBLAST investigations have focused on the role of swell on momentum exchange under low wind conditions while the CLIMODE investigations have focused on momentum exchange at high winds. This investigation focuses on heat exchange from low to high winds using the combined data sets. Preliminary results from this investigation were reported at the AMS 17th Conference on Air-Sea Interaction in Annapolis, MD.

RESULTS

The CBLAST measurements indicate that the directly measured fluxes are somewhat lower than C3.0 when the latent heat flux is positive (corresponding to an upward moisture flux), but are significantly different than C3.0 when the latent heat flux is negative (corresponding to a downward moisture flux). The downward latent heat flux is often associated with fog and stable conditions. However, the CBLAST data indicates that the Dalton number (i.e., the transfer coefficient for latent heat) is still smaller that C3.0 even after removal of downward fluxes and foggy periods. This is in good agreement with the results from both the CLIMODE and GASEX programs as shown in Figure 1.

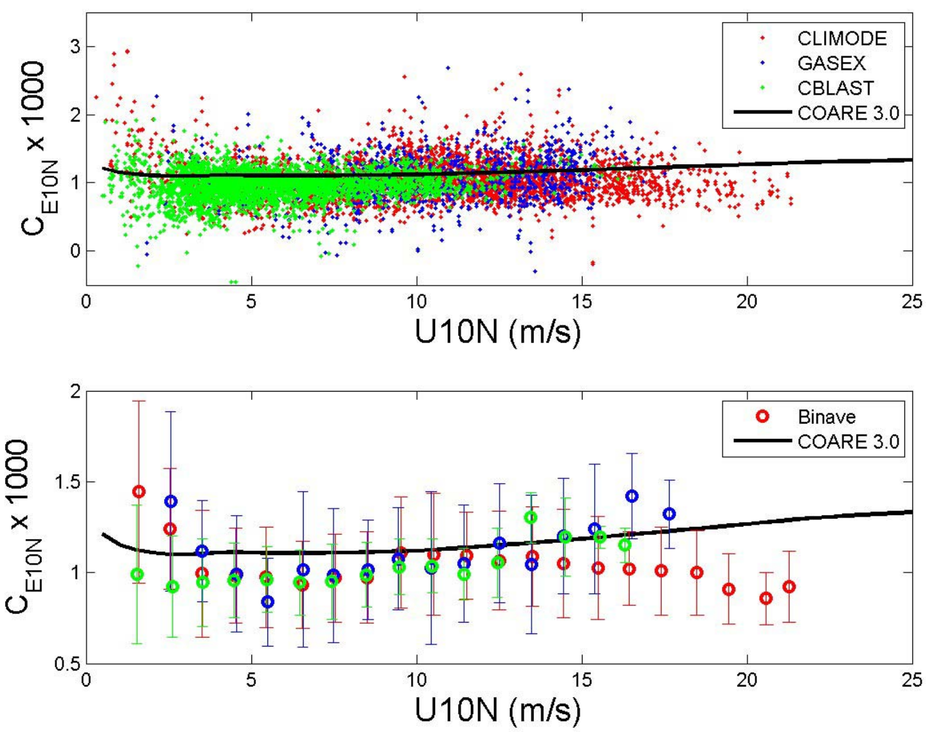

Figure 1. Bin-average estimates of the neutral Dalton number using latent heat fluxes measured during the CBLAST, CLIMODE and GASEX programs.

Therefore, the COARE 4.0 algorithm proposes a neutral Dalton number that is 20% lower than the COARE 3.0 algorithm at low to moderate wind speeds. However, there are significant differences between the data sets at moderate to high winds

On the other hand, the Stanton number (i.e., the transfer coefficient for sensible heat) is in reasonable agreement with COARE 3.0 below 15 m/s for all three data sets as shown in Figure 2. This result argues against the commonly held assumption that the neutral transfer coefficients for heat and mass are equal. However, there is significantly more scatter in these results and the CBLAST and GASEX results again show different behavior at unstable versus stable data (not shown).   Validation of the reduced Dalton number, confirmation of the observation that heat and mass transfer coefficients are not equal, and reduction of the uncertainty in these parameterizations is anticipated from the carefully conducted measurements we expect from the field program.

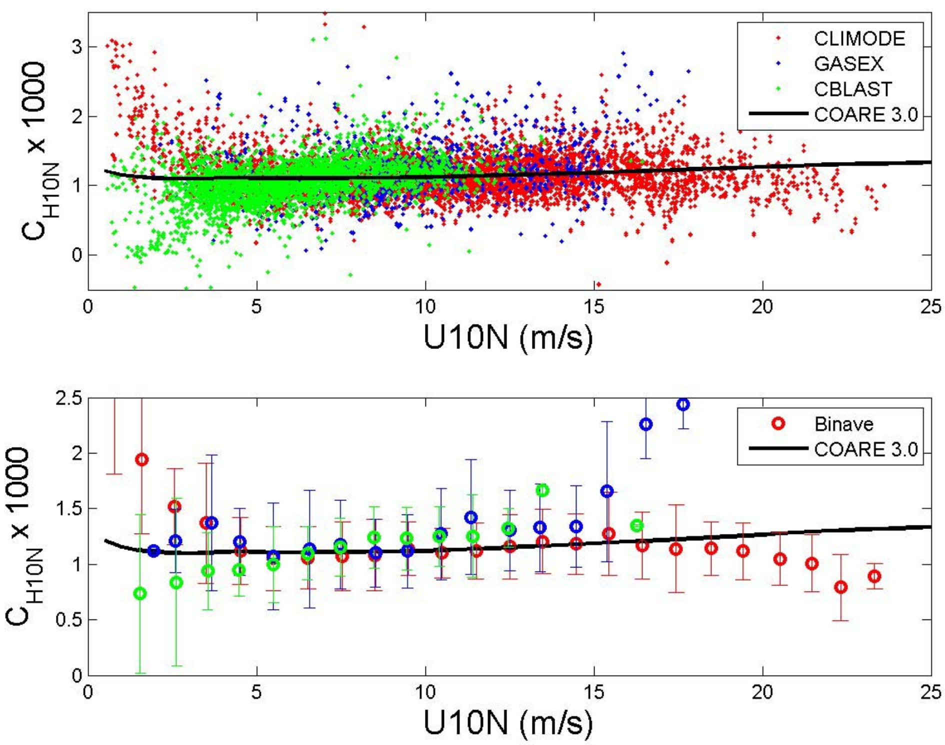

Figure 2. Bin-average estimates of the neutral Stanton number using sensible heat fluxes measured during the CBLAST, CLIMODE and GASEX programs.

IMPACT/APPLICATIONS

None to date

TRANSITIONS

None to date

RELATED PROJECTS

The ONR portion of this program will work closely with investigators from the NSF/NOAA funded DYNAMO program.

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PUBLICATIONS RESULTING FROM THIS PROPOSAL

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